The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation

J. Bader

Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany

Max-Planck-Institute for Meteorology, Hamburg, Germany

M. Latif

Institute for Marine Research at the University of Kiel, Kiel, Germany

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[1] The sea surface temperatures (SSTs) of the tropical Indian Ocean show a pronounced warming since the 1950s. We have analyzed the impact of this warming on Sahelian rainfall and on the North Atlantic Oscillation (NAO) by conducting ensemble experiments with an atmospheric general circulation model. Additionally, we investigate the impact of the other two tropical oceans on these two climate parameters. Our results suggest that the warming trend in the Indian Ocean played a crucial role for the drying trend over the West Sahel from the 1950s to 1990s and may also have contributed to the strengthening of the NAO during the most recent decades. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation. **Citation:** Bader, J., and M. Latif, The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation, *Geophys. Res. Lett.*, *30*(22), 2169, doi:10.1029/2003GL018426, 2003.

1. Introduction

[2] The climate of the 20th century exhibited some rather strong decadal-scale changes. One example is the drying trend in the Sahelian region from the 1950s to the 1990s (Figure 1a). Another is the strengthening of the North Atlantic Oscillation [NAO, *Hurrell*, 1995], the leading mode of North Atlantic climate variability, from the 1970s onward (Figure 1b). Both phenomena are the subject of many observational and modelling papers [e.g., *Folland et al.*, 1986; *Hurrell et al.*, 2003 and articles therein], but it remains controversial which processes lead to the decadal climate fluctuations. We address in this paper the role of the tropical Indian Ocean SST in driving these changes, since the tropical Indian Ocean SST exhibits a remarkable warming trend during the last 50 years (Figure 1c).

[3] The regions north and south of the Sahara desert are regions with climates that are among the most variable in the world [*Ward et al.*, 1999]. The Sahelian region is located south of the Sahara desert, defined here as the latitudinal band spanning the African continent from 12°N to 20°N. The rainy season is from June to September (JJAS) and associated with the seasonal movement of the intertropical convergence zone (ITCZ). The West Sahel JJAS rainfall index (defined from 10°W to 10°E and from 12°N to 20°N - indicated by the box in Figures 2b, and 3a–3c) shows a strong decadal trend. There was anomalously strong rainfall in the 1950s and early 1960s (wet mode), followed by an extended anomalously dry period since the 1970s (dry mode) (see Figure 1a) that had and continues to have important economic and social impacts. Observational and model studies show that Sahelian rainfall variability is associated with regional and global SST anomaly patterns. These include changes in the tropical Atlantic [e.g., *Lamb*, 1978a, 1978b; *Hastenrath*, 1984; *Lamb and Peppler*, 1992; *Ward*, 1998; *Vizy and Cook*, 2001, 2002], in the Pacific [e.g., *Janicot et al.*, 1996; *Rowell*, 2001], in the Indian Ocean [*Palmer*, 1986; *Shinoda and Kawamura*, 1994], and in the Mediterranean [*Rowell*, 2003]. *Folland et al.* [1986] linked near global changes in sea surface temperatures to Sahelian rainfall variability. In the first part of this paper, we investigate the impact of tropical SSTAs on the low-frequency variability of sub Saharan rainfall by conducting a series of experiments with an atmospheric general circulation model (AGCM). We investigate the role of the different tropical ocean basins and their combinations in forcing decadal Sahelian rainfall anomalies.

[4] In the second part of our study, the model experiments with our atmospheric general circulation model are analyzed with regard to the impact of tropical SSTs on the extratropical climate, specifically the NAO. The NAO shows strong interannual and decadal variabilities during the last century (Figure 1b). Different hypotheses were put forward to explain the low-frequency changes of the NAO. Internal atmospheric dynamics were suggested by *James and James* [1989]. *Saravanan and McWilliams* [1997] linked the low-frequency variability to a stochastic forcing of the atmosphere driving low-frequency changes in the ocean which feed back on the atmosphere. In AGCM experiments, *Rodwell et al.* [1999] and *Latif et al.* [2000] found an oceanic control of decadal North Atlantic sea level pressure variability in winter. *Hoerling et al.* [2001] linked the recent trend of the NAO to a warming of the tropical oceans. Our study investigates not only whether the recent decadal change of the NAO is of tropical origin, but also which tropical ocean basin contributed most to the change. We focus on the role of the tropical Indian Ocean, since it

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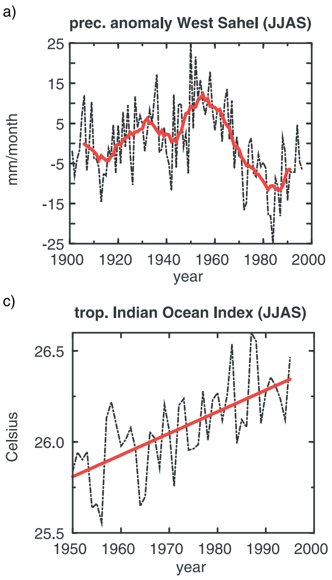

Figure 1. a) Observed JJAS rainfall anomaly over the West Sahel, based on the Climate Research Unit dataset (mm/month), b) observed winter (DJFM) NAO index defined by *Hurrell* [1995], c) observed tropical Indian Ocean SST Index for the JJAS season (in Celsius), based on the Reynolds SSTs; averaged from the east coast of Africa to 120°E and from 30°S to 30°N. The black curves denote the seasonal means, the red curves the 11-yr running mean or the linear trend.

exhibits a rather gradual warming trend during the recent decades (Figure 1c).

2. Model and Experiments

[5] We use the atmospheric general circulation model ECHAM4.5 [*Roeckner et al.*, 1996]. The model forced by the observed SSTs from 1951 to 1994 reproduces the decadal trend of Sahelian rainfall [*Schnitzler et al.*, 2001] and simulates the observed low-frequency NAO index variations reasonably well [*Latif et al.*, 2000]. As described above, rainfall over the West Sahel shows a multidecadal drying trend from the 1950s (wet mode) to the beginning of the 1990s (dry mode). The wet and dry modes are defined here as the periods from January 1951 to December 1960 and from January 1979 to February 1996, respectively. We examine the decadal-scale response of ECHAM4.5 to the observed tropical SST anomaly field representing the difference between the dry and wet mode. The model's response to the total SST forcing, its individual components in the different ocean basins and combinations of these are analyzed. Figure 2a shows the tropical (30°S–30°N) SST difference field (here for the June to September (JJAS) season) contrasting the situations between the dry and wet mode in the Sahel. In the 1950s, the tropical SSTs were considerably colder relative to the 1980s and 1990s, and we address the impact of these anomalously cold tropical SSTs on Sahelian rainfall and the NAO. Please note that the strongest cold anomaly is found in the tropical Indian Ocean, and we are here mostly concerned with the impact of this anomaly on the tropical and Northern Hemisphere climate. In the dry mode experiment, the clima-

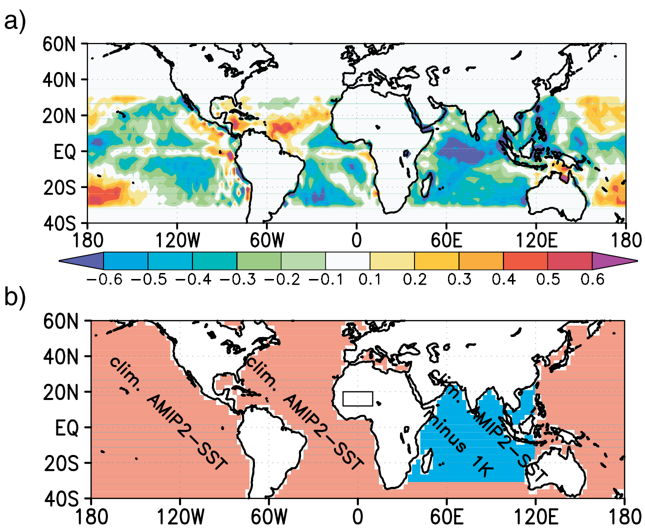

Figure 2. a) SST difference field: JJAS SST anomaly in the tropics (Wet-Mode (1951–1960) minus Dry-Mode (1979–1995)) (in Kelvin) and b) SST anomaly for the "Indian Ocean minus 1K" experiment (in Kelvin).

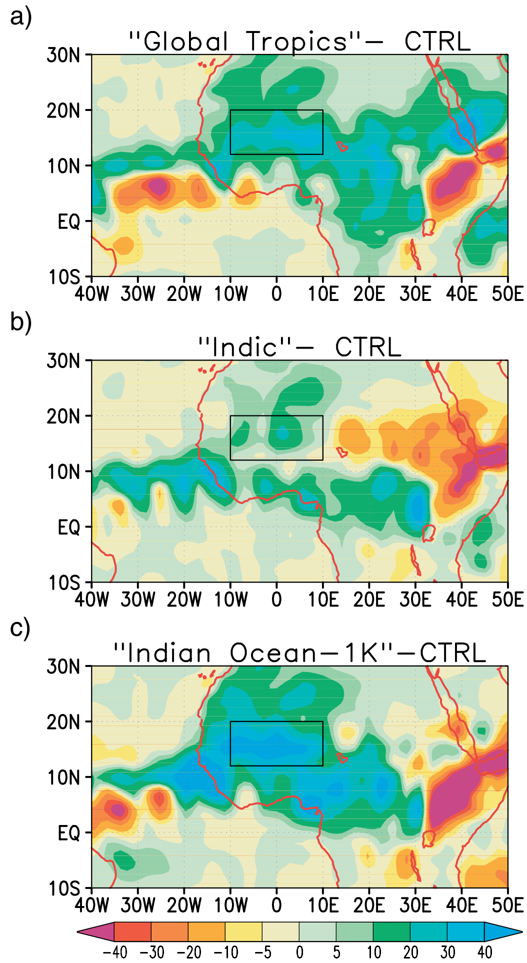

Figure 3. a) Simulated JJAS rainfall anomaly (relative to control integration) for the experiments with: Full SST anomaly of Figure 2a ("Global Tropics"); b) Indian Ocean portion of Figure 2a ("Indic"); c) SST anomaly of Figure 2b ("Indian Ocean minus 1K"); units: mm/month; the box indicates the West Sahel.

tological AMIP2-SST [*Taylor et al.*, 2000] is used, while in the wet mode experiment, the climatological monthly means are computed from the Reynolds SSTs (Reynolds SST data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/). Results are obtained from a set of 21-year long SST sensitivity experiments. The results are averaged over the last twenty years and only the mean response (sensitivity run minus control integration) is shown here.

[6] The integrations are as follows: The control integration is driven with the climatological AMIP2-SST (dry mode). In the integration ''Global Tropics'', the full SST anomaly field of Figure 2a is added to these values. In the integrations ''Atlantic'', ''Pacific'', and ''Indic'' only the SST anomalies in Figure 2a from the respective ocean basins are added to the climatological AMIP SSTs of the control run.

3. Results

[7] In the experiment ''Global Tropics'', the tropical SSTs are changed according to Figure 2a in order to simulate the situation in the 1950s. Consistent with the observations, the tropical SST anomalies produce a precipitation increase in the whole sub-Saharan Sahel region (Figure 3a). In particular, the response is significant according to a two-sided t-test at the 95%-confidence-level over the West Sahel (indicated by the box). Over the tropical Atlantic, the model simulates a northward shift of the intertropical convergence zone (ITCZ), with more rainfall in the north and less in the south.

[8] Next we investigate the rainfall response to the SST anomalies in the individual tropical ocean basins. In the ''Atlantic'' integration, the rainfall response is primarily characterized by a rainfall decrease over southern West Africa and the eastern tropical Atlantic. Over the West Sahel significant less rainfall is simulated (not shown). In the ''Pacific'' experiment, a positive rainfall anomaly is simulated over the eastern Sahel but not over the western Sahel, and the maximum rainfall anomaly is located close to the Red Sea (not shown). In the ''Indic'' experiment, the rainfall is enhanced over West Africa, the ITCZ is intensified over the tropical Atlantic Ocean, and the rainfall is reduced over East Africa (Figure 3b). Please note that the rainfall enhancement over West Africa is associated with an intensification of the ITCZ and not with a meridional shift. Thus, the Indian Ocean SST anomalies appear to be most important forcing in driving the decadal drying trend in the West Sahel. The results of considering the SST forcing in two ocean basins together (not shown) confirm the importance of the tropical Indian Ocean for the decadal rainfall change over the West Sahel. Tropical Atlantic SST anomalies with either the tropical Pacific or Indian Ocean SST anomalies produces nearly the same rainfall anomalies over North Africa as the Pacific or Indian Oceans alone. The main influence of the tropical Atlantic Ocean is on the Atlantic coastal regions and over the Atlantic Ocean itself. The ''Pacific/Indic'' experiment produces a similar rainfall response as the ''Global Tropics'' experiment over the Sahel.

[9] Thus, our SST sensitivity experiments indicate that the Pacific Ocean is the most important agent in producing the decadal rainfall reduction over the East Sahel while the tropical Indian Ocean drives the anomalies over the West Sahel. As described above, the SST of the Indian Ocean shows a pronounced warming since the 1950s. In order to further investigate the role of the Indian Ocean SST, the tropical Indian Ocean SST of the control integration is reduced by one Kelvin (see Figure 2b) in an additional sensitivity experiment to ''mimic'' the 1950s. Again, significant JJAS rainfall enhancement over West Africa is obtained (Figure 3c) confirming our hypothesis that the tropical Indian Ocean plays an important role in forcing Sahelian rainfall anomalies. Further analyses of the experiments provide the following picture: The reduced SSTs in the tropical Indian Ocean lead to less convection/precipitation over most of the tropical Indian Ocean. This results in an anomalous downward motion, reduced latent heat release, and upper tropospheric convergence. The anomalous inflow results in anomalous westerly winds over Africa. This anomalous east-west circulation in the upper atmosphere links the region of anomalous convergence over the Indian Ocean to the region of anomalous divergence centered over West Africa. The latter is connected with upward motion over West Africa, and the enhanced convection is amplified by enhanced moisture convergence and convective heating. Next, the experiments are analyzed with regard to the impact of tropical sea surface temperatures on the Northern Hemisphere winter (December to February (DJF)) climate, specifically the changes of the North Atlantic Oscillation. The NAO exhibits a strong upward trend since the 1970s and a reverse trend in the 1950s and 1960s [*Hurrell*, 1995]. In the ''Global Tropics'' experiment, a weakening of both the Icelandic low and the Azorian high is simulated (Figure 4a), which results in a weakening of the NAO and is in agreement with the observations. Thus, our experiment indicates that the decadal trend of the NAO in the recent decades contains a tropical SST forced component, a result that is consistent with findings of *Hoerling et al.* [2001]. *Hoerling* [2001], however, did not consider the impact of the individual tropical ocean basins on the NAO. The results of our experiments with the SST forcing restricted to individual ocean basins and combinations of these show the strongest impact on the NAO from the Indian Ocean (Figure 4b). The sensitivity experiment, in which the tropical Indian Ocean is simply reduced by one Kelvin (Figure 2b) shows a similar NAO response as the ''Global Tropics'' and ''Indian Ocean'' experiments (Figure 4c). A t-test indicated that the results are significant at the 95%-confidence-level in all three experiments, at least in the centers of action. These experiments indicate that the warming of the Indian Ocean during the last decades seems to be of large importance for the strengthening of the NAO.

4. Summary

[10] In summary, we find by conducting a set of numerical experiments with an atmospheric general circulation model that the warming of the Indian Ocean in the last decades is of paramount importance in driving the observed decadal drying trend over the West Sahel. We find additionally that the warming of the tropical Indian Ocean may have also contributed to the strengthening of the NAO observed during the recent decades.

[11] The role of the tropical Indian Ocean SST in driving Sahelian rainfall anomalies is supported by relatively high

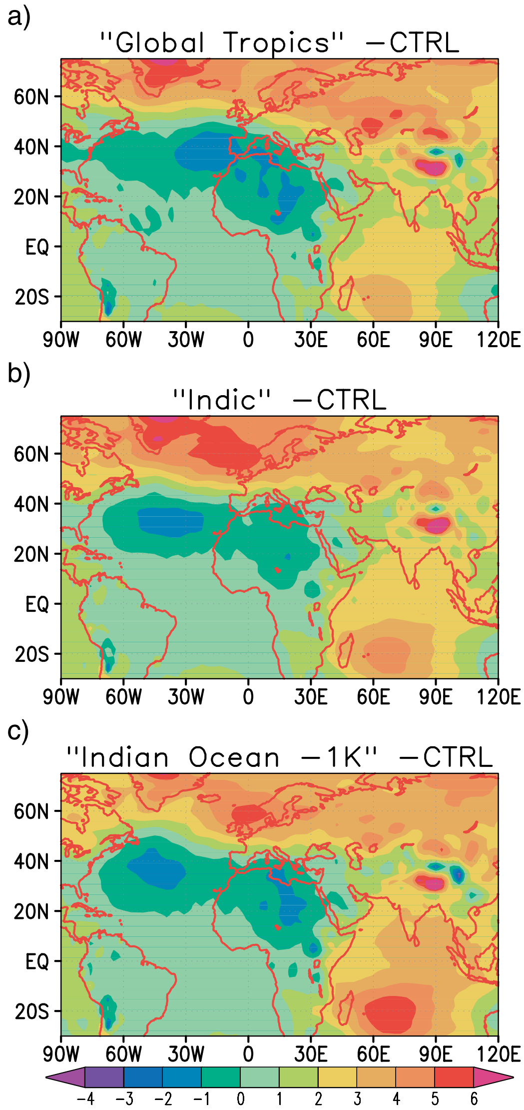

Figure 4. a) Simulated DJF sea level pressure (SLP) anomaly (relative to control integration) for the experiments with: Full SST anomaly of Figure 2a ("Global Tropics"); b) Indian Ocean portion of Figure 2a ("Indic"); c) SST anomaly of Figure 2b ("Indian Ocean minus 1K"); units: hPa.

anti-correlations between the observed low-pass-filtered rainfall over the West Sahel and tropical Indian Ocean SSTs and by an observational study of *Shinoda and Kawamura* [1994]. According to our experiments, the tropical Pacific's influence is predominantly over the East Sahel. The tropical Atlantic impacts rainfall only over the Atlantic itself and along its coasts, e.g., the Guinea Coast. Furthermore, our experiments confirm the hypothesis that the recent decade-long strengthening of the NAO is at least partly of tropical origin. We conclude that the Indian Ocean SSTs play an important role not only in forcing regional climate anomalies [e.g., *Latif et al.*, 1999] but also in driving extra-tropical climate anomalies.

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J. Bader, Max-Planck-Institute for Meteorology, Hamburg, Bundesstraße 55, Hamburg, 20146, Germany. (bader@dkrz.de)

M. Latif, Institute for Marine Research at the University of Kiel, Kiel, Germany.